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13. ABSTRACT (Maximum 200 words)

A new finite element time dependent, two dimensional magnetofluid code has been written. This code offers the possibility of localized mesh refinement to capture the development of current sheets, analogous to shocks by hydrodynamics. The finite difference MHD code was improved during the past year. The code is now robust, fast and user friendly. Fast driven magnetic reconnection has been simulated in three dimensions and the reconnection time scale is consistent with one logarithmic in the plasma resistivity. A model has been found where a spontaneous discontinuous magnetic field develops from a continuous initial state, which phenomenon is believed to occur in the solar corona. Several theories of MHD and resistive MHD instabilities in the solar corona have been developed.

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1992 RESEARCH REPORT

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Publications

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Work Description

New Finite Element Numerical MHD Code

We have written a new finite element time dependent, two dimensional magneto fluid (MHD) code. The elemental cells of the mesh are triangles, which offer both simplicity and adaptability. This approach is considered the state of the art in aerodynamics and fluid dynamics. Our code represents one of the first efforts to apply this method to MHD. It offers the possibility of localized mesh refinement, to capture the development of current sheets, analogous to shocks in hydrodynamics. Current sheets have a fundamental role in MHD instability and fast magnetic reconnection.

The finite element method divides the computational domain into discrete, non overlapping elements. The partial differential equations are replaced with matrix equations by expanding the variables in basis functions. The most convenient basis fuctions are piecewise linear "tent" functions, which are non zero at a vertex common to several triangles, and which vanish at all other vertices. Choosing elements which vanish on the boundary and integrating by parts leads to matrix equations. The matrices are sparse, since the elements are non zero only on the triangles which include a particular vertex.

Direct solution of these matrix equations is impractical because of storage requirements. The preferred method is the conjugate gradient method, which has no parameter. It converges rapidly if *preconditioned* to make the ratio of smallest to largest eigenvalues of the matrix as close to unity as possible. A popular preconditioner is the *incomplete Cholesky* decomposition. The complete Cholesky decomposition is equivalent to inverting the matrix, while the incomplete Cholesky decomposition is equivalent to an approximate inverse with the same sparsity as the original matrix. We solve the matrix equations using an Incomplete Cholesky Conjugate Gradient algorithm.

Preliminary tests of the code are encouraging. We have reproduced existing simulations of the resistive internal kink mode and the two dimensional tilt instability.

We have introduced an implicit method for calculating highly anisotropic heat flow. This could be applied to simulations of prominence formation.

We have several mesh refinement schemes implemented and are working on adaptively refining the mesh as the solution evolves, packing in more triangles in regions of enhanced current.

The present code is two dimensional, but we intend to extend it to three dimensions.

Finite Difference MHD Code

This code, developed previously, was improved greatly during the past year. A recentering of the velocity on the staggered mesh improved the numerical stability by eliminating a mild alternating instability. The code is now quite robust, fast, and user friendly. We applied it to linear and nonlinear computations of the coalescence instability, which are described below.

Fast Three Dimensional Reconnection

Fast driven magnetic reconnection has been simulated in three dimensions. The numerical results are consistent with a reconnection time scaling as $\log \eta$, where η is the plasma or fluid resistivity. This is a first, both in obtaining the scaling and in doing it in three dimensions. This result is essential if solar flares are to be explained in terms of magnetic reconnection. Flares occur on such a short time scale that reconnection must proceed at a rate only weakly dependent on resistivity.

This scaling of reconnection time was proposed by Petschek in 1964, but the detailed behavior of the reconnection process appears different from his model. In Strauss (1993), an analytic model is presented along with the simulations showing how this scaling can arise. The model is in reasonable agreement with the numerical results.

The computational model is a long thin flux tube between conducting ends, representing the intersection of coronal magnetic field lines with the solar photosphere. A driving flow is applied on the boundaries which sets up a three dimensional flow pattern in the flux tube and forces magnetic field lines to reconnect. The spatial peak of current occurs along the stagnation line of the flow. The spatial peak current increases exponentially in time, until it saturates at a peak temporal value. After this time, it decays. The time of spatial and temporal peak current is identified as the reconnection time. It is measured in numerical runs with resistivity η varying over $2\frac{1}{2}$ orders of magnitude, and all other parameters held constant. This gives a reconnection time $\sim \log \eta$, or perhaps as $\eta^{0.05}$. The former is preferable, because we have a theory for the scaling and time dependence of the simulations.

We hope to do further simulations in which the driving velocity is also varied. We want to see how the reconnection rate depends on the driving velocity. If the velocity is small, we should obtain a Sweet - Parker like reconnection time scaling as $\eta^{1/2}$. At larger velocities it should tend to our Petschek like scaling.

Singular Equilibria and the Coalescence Instability

There has been a great deal of recent interest in the spontaneous development of discontinuous magnetic fields from a continuous initial state. Such a scenario is thought to occur in the solar corona both during flare events where it leads to observed rates of magnetic reconnection, and during more quiescent periods where it results in enhanced rates of MHD energy dissipation. We have found a model in which such an event occurs.

We begin with a two dimensional force-free magnetic equilibrium consisting of a doubly periodic array of magnetic islands. These islands surround smooth current channels which also form a doubly periodic array and which alternate in sign. It can be shown that this equilibrium is unstable; a small perturbation to the plasma will cause neighboring islands with parallel currents to accelerate towards one another. As in the more conventional coalescence instability the source of free energy here is the mutual attraction of parallel currents.

Using a nonlinear time-dependent numerical simulation we demonstrate that the initial attraction continues until the magnetic field reaches a new stable equilibrium. This simulation solves ideal equations so that no magnetic reconnection occurs. As a consequence the initial pattern of magnetic islands must be preserved in the new equilibrium. The new equilibrium can be approximated analytically by seeking a minimum of the magnetic energy subject to some constraints. We show that admitting magnetic fields with discontinuities leads to an equilibrium with the same field line topology as the initial condition, but with a magnetic energy 2.8% lower. This equilibrium closely resembles the final state of the time dependent simulation, but for numerical reasons the latter is precluded from having true discontinuities.

This simple example demonstrates that it is possible to have multiple equilibria consistent with a single magnetic topology, and for some of the equilibria to be discontinuous. The energetically unfavorable equilibria will be dynamically unfavorable, and discontinuities will therefore develop spontaneously as the field relaxes to the most favorable state.

MHD Instabilities in the Solar Corona

We developed several analytic theories of MHD and resistive MHD instabilities in the solar corona. In Meytlis and Strauss (1992) we found convection driven unstable by a temperature gradient transverse to the magnetic field. This instability could occur at the edge of a sunspot, which is penetrated by a strong magnetic field and is cooler than its surroundings. Unlike conventional convection, this convection generates vorticity aligned with the magnetic field. This is very important, because coronal heating theories like Parker's 1972 model require this kind of vorticity to braid magnetic field lines. This is a possible mechanism to cause this magnetic braiding.

We also considered line tied Rayleigh Taylor instabilties in prominences (Strauss and Longcope, 1993). We started with a new two dimensional prominence model, which generalizes the Kippenhahn Schlüter model. We then analyzed its stability and found that the instability condition can be expressed in terms of the angle between the magnetic field and the prominence axis. As ths angle decreases, the prominence gets more unstable. This is very suggestive of the data indicating a relationship between magnetic shear in arcades and solar flares. Increasing the shear decreases the angle. Our calculation assumed short wavelengths, so our instability might describe the irregular "rain" falling from prominences. If there is a long wavelength version of the instability, it might also describe prominence eruptions! We would like to perform numerical simulations to test this idea.

The Hall effect on reconnection was explored by Fruchtman and Strauss (1993). It was found that the growth rate of the tearing mode is greatly increased in regimes where the Hall effect is important. This might play a role in fine scale MHD turbulence.

Approximate Long-Thin Plasma Equilibrium Solutions (E. Hameiri, R. Young)

The typical magnetic configuration in the corona, the coronal flux tube, is much longer than it is wide with a typical aspect ratio of 10:1. We have constructed such equilibrium states based on the long-thin approximation. Our method works both for 2D and 3D configurations. The 2D situation is also applicable to the geo-magnetotail. We have incorporated into the equilibrium state mass flow parallel to the magnetic field as is experimentally observed, and were able to describe plasmoids moving down the magnetotail. To our knowledge, this is the first working plasmoid solution in the literature (published in *JGR*, 1992). The plasmoid shape, whether cusped or with round edges, depends intimately on the profile of the total pressure (thermal plus magnetic) which is imposed by the surrounding medium. We give precise criteria for the resulting plasmoid shape which are borne out by numerical calculations. At present, we already have the method used for 3D solutions, and will apply it to coronal flux tubes, where a breakdown in the solution may correspond to a solar flare.

Ballooning Modes in Fluids and Plasmas (E. Hameiri, A. Lifschitz, M. Mond)

The differential rotation of the sun is indirectly responsible for the generation of the solar magnetic field. The rotation frequency profile, as one looks into the solar interior, cannot be arbitrary but must obey some constraints such as stability. We have investigated a particular class of instabilities, the analog of ballooning modes in plasmas, which were discovered by us to exist even in the absence of a magnetic field. For classical fluids these modes are localized to streamlines and are akin to the Rayleigh-Taylor instability. Last year we reported on the stability of very simple configurations, such as those with stagnation points. More recently, in a series of papers, we have dealt with more general configurations. For steady flows we distinguish between two types of streamlines: (a) Beltrami streamlines, where the vorticity is parallel to the velocity, (b) non-Beltrami streamlines. We prove that in the generic case the non-Beltrami streamlines have algebraically growing modes while the Beltrami streamlines may have exponentially growing modes. In particular, we show that all generic axisymmetric toroidal configurations (vortex rings) are exponentially unstable.

A configuration of particular interest is when the rotation is purely toroidal, as in the solar interior and other stars. The simplicity of this case allows for the derivation of exact stability criteria, even when the effect of gravity is included. In the absence of a magnetic field we recover the previously known Høiland stability criterion. If a magnetic field is present the criterion is much more complicated, and this is being presently pursued. We consider in particular the case of a purely toroidal magnetic field. It appears that for a large enough field, all non-axisymmetric modes will be stable. However, there may still be a window of instability for the axisymmetric modes if the Rayleigh-Taylor drive is sufficiently strong.

Meetings and Laboratory Visits

We attended the American Physical Society Meeting in November, 1992. We visited the National Solar Observatory at Sacramento Peak, New Mexico, in May, 1992. We gave a presentation and spoke with Dr. Don Neidig, Dr. Steve Keil, Dr. Jack Zirker, and other memebers of the observatory staff. This was combined with a visit to Dr. Tom Hussey and his group at Phillips Laboratory, Kirtland AFB, Albuquerque. We also had a presentation at the Solar Physics section of the American Astronomical Society meeting.

Figure Captions

Fig. 1 – A surface plot of current vs. position in the x, y plane, during the nonlinear phase of the coalescence instability described in the report. The "shark fins" are current sheets.

Fig. 2 – The magnetic flux function corresponding to the current in the previous figure. In the initial state, the cells are square. The instability pushes cells toward each other, flattening a corner of each cell. The sharp, intense currents occur at the short sides of pentagonal cells.

Fig. 3 – An unstructured mesh used by our new MHD code. The local mesh refinement gives the possibility of resolving localized intense currents produced by MHD instability or forced reconnection, even when these currents occur at arbitrary spatial locations.

Fig. 4 – A current sheet in a driven three dimensional reconnection simulation, discussed in the report. Shown are contours of current in the x, y plane at constant axial coordinate z. The current spike in the center is associated with rapid magnetic field reconnection.

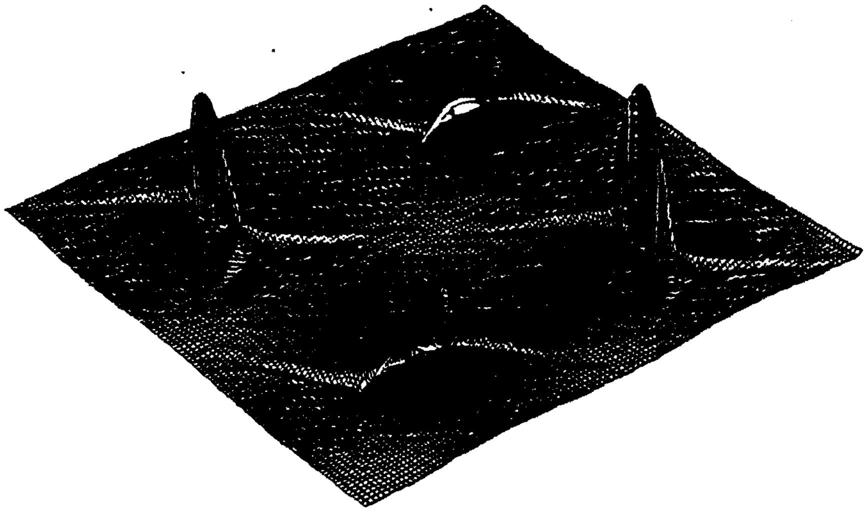

Fig. 1

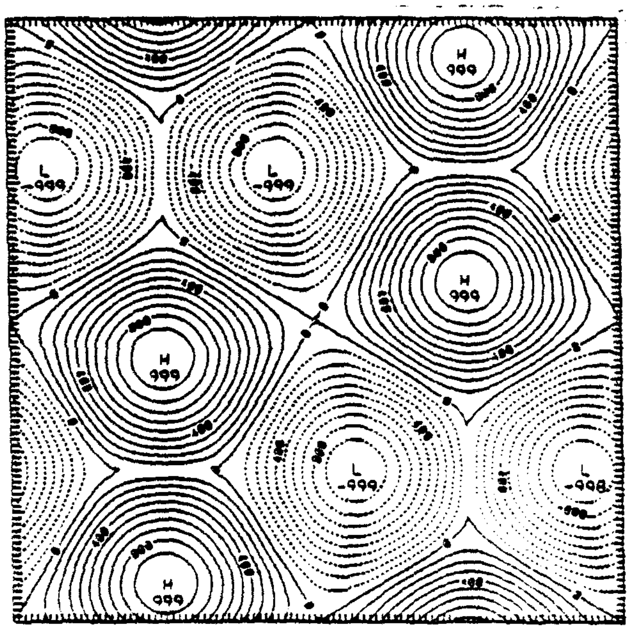

Fig. 2

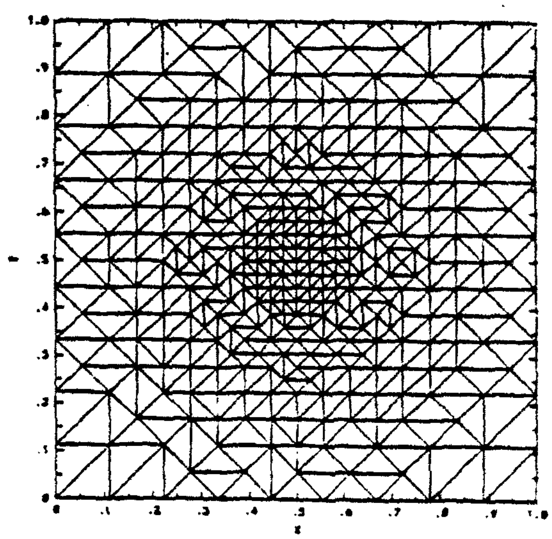

Fig. 3

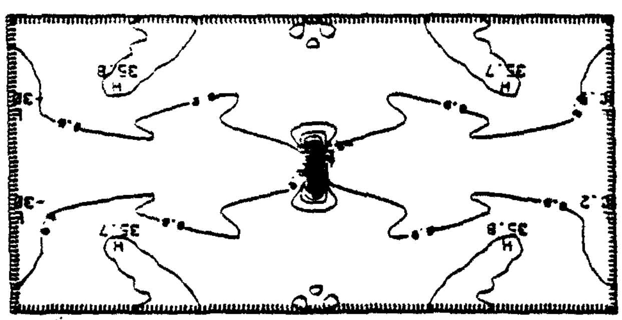

Fig. 4